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Phosphorus uptake during four years by different vegetative cover types in a riparian buffer

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Abstract Vegetative buffers have been shown to reduce nutrient loss associated with the transport of detached soil particles and may through plant uptake offer a means to capture dissolved nutrients moving to surface waters through the soil solution. The objective of this 4-year study was to evaluate changes in the biomass and P content of the roots and shoots of plants growing in a multi-species versus a single species riparian buffer as an index of P capture potential. Periodic harvests of above ground vegetation were combined with root cores to estimate the total standing biomass and the pool of P in plant tissue in three vegetative cover types dominated by either switchgrass (*Panicum virgatum* L.), an alfalfa (*Medicago sativa* L.)-smooth bromegrass (*Bromis inermis* Leyss) mix, or a fast growing superior cottonwood (*Populus deltoids* Bartr., clone 42-7). An existing stand of smooth brome served as the single species control. Standing biomass increased in all three cover types during the 4 years of study, with the greatest increases observed in the cottonwood (2345 g m^{-2}) and switchgrass (1818 g m^{-2}). Biomass production in the smooth brome control did not change during the study period. Based on the 4th-year samples, standing pools of P closely paralleled total plant biomass and root surface area with cottonwood accumulating the greatest amount of P at 19.4 g m^{-2} compared to 4.3 g m^{-2} for the smooth brome control. Estimates of potential P export via biomass harvest from a mixed buffer over a 4-year interval were 101 kg ha^{-1} compared to 62 kg ha^{-1} for the smooth brome control; a 63% increase in export capacity due largely to the inclusion of cottonwood. Addition of a fast growing woody species combined with periodic biomass harvests has the potential to reduce P movement to surface waters.

Keywords Cottonwood · Phosphorus · Plant biomass · Smooth Brome · Switchgrass

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Introduction

Land management practices that produce soil disturbance or include nutrient amendments are thought to contribute disproportionately to increasing levels of P in surface waters (Sharpley

et al. 2000). This growing risk of eutrophication of surface waters has made the reduction of P export from agricultural land an urgent matter (Torrent and Delgado 2001). Soil conservation practices can substantially reduce P inputs to surface waters from particulate sources (Withers and Jarvis 1998; Quinton et al. 2001). Control of dissolved P export is more problematic because the range in soluble P can vary among sites. For example, Allen et al. (2006) report water extractable P in five Mid-western soils to range from 2 to 568 mg P kg^{-1}. In the same study, total P, as determined by an alkaline oxidation procedure, ranged from 374 to 689 mg kg^{-1}. We know that plant uptake has the potential to reduce P concentration in soil solution and thus reduce the movement of dissolved P into surface waters. We also know that differences in plant species, type, and age can influence nutrient uptake and retention. Gatibone et al. (2005) found that after 15 cropping cycles total P (by acid digestion) in Brazilian Oxisols and Ultisols declined by approximately 20% even with the addition of P. Plant available P after 15 cropping cycles exhibited a greater degree of response to added P, but still declined by as much as 50% (Gatibone et al. 2005). In contrast, Soon and Arshad (1996) found no change in soil P under a continuous forage bromegrass stand over a 23-year interval. A potential limitation of a plant-based approach to P capture that does not include plant harvest and removal is the likelihood that the plant community will come to equilibrium in biomass production after a period of time and thus become less effective in capturing solution P. Although not currently permitted by most government subsidized riparian buffer programs, a management approach that allows removal of accumulated vegetation would restart the accumulation process and help sustain P capture over the longer term.

Using P in the standing biomass as an index, the objective of this study was to assess biomass production and P uptake of three vegetative components of a multi-species riparian buffer during the first four growing seasons. For comparative purposes biomass production and P uptake occurring in an adjacent established single-species buffer were also measured.

Materials and methods

Site description

The study was conducted at the USDA-ARS Deep Loess Research Station located in the Loess Hills region of western Iowa. In the Spring of 2001, a multi-species riparian buffer was established along the west side of an existing drainage way, extending 200 m downstream. Prior to the establishment of the buffer, the study area had been in a continuous corn-soybean rotation for more than 30 years. The buffer consisted of a 5-m wide strip of switchgrass directly adjacent to the crop land, a 5-m wide intermediate strip of alfalfa mixed with smooth brome, and a 15-m wide strip containing four rows of fast growing superior cottonwood adjacent to the drainage way (Fig. 1). The long axis of all three cover types paralleled the drainage way. The herbaceous strips were planted with a tractor-drawn drill and the cottonwoods were planted by hand as rooted cuttings on April 13, 2001. A 3×3 m spacing

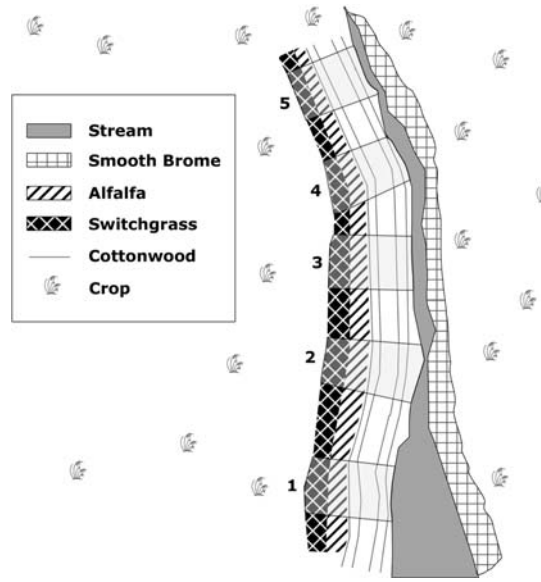

Fig. 1 Schematic representation of the study site indicating the relative position of the smooth brome, alfalfa, switchgrass, and cottonwood vegetative cover types at the USDA-ARS Deep Loess Research Station. Relative locations of the five sampling blocks are also identified

was used for the cottonwoods. The width and relative location of the vegetative strips was based on USDA Natural Resource Conservation Service design criteria derived from the work of Schultz et al. (1995, 2000). Stand establishment in the alfalfa–smooth brome mix was spotty in the first year and was replanted in the spring of 2002. The underlying soil was mapped as a Kennebec silt loam (Fine-silty, mixed, superactive, mesic Cumulic Hapludolls) with a slope of 0–2%.

For comparative purposes, the opposing (east) side of the drainage way was left in an established stand of smooth brome that had been in existence since 1964. The smooth brome buffer varied in width from 5 to 7 m along the length of the drainage way (Fig. 1). A deeply incised gully extended down the center of the drainage way, and surface flow was visible in the gully during the majority of the study period. Soil on the east side of the study site was mapped as a Napier silt loam (Fine-silty, mixed, superactive, mesic Cumulic Hapludolls) with a 2–5% slope.

Sampling of above ground biomass

For sampling purposes, the study site was divided into five 22×20 m blocks arrayed along and perpendicular to the long axis of the buffer (Fig. 1). On each sampling occasion two samples for biomass determination were collected at random locations within each of the herbaceous cover types within each of the blocks. Above ground biomass samples were collected prior to senescence at the end of the 2001, 2002, 2003, and 2004 growing seasons. The alfalfa–smooth brome cover type was not sampled in 2001 due to poor stand establishment. In addition to the mid-September samples collected near the end of the growing season each year, a more intensive sampling schedule was used in 2003, with samples also collected in mid-May, early July, and mid-August.

For the herbaceous cover types, quarter meter plots were clipped, bagged, and returned to the laboratory for oven drying at 60°C for 48 h. Following dry weight determination, sub-samples were ground in a Wiley mill using a 1-mm screen and stored in sealed plastic jars.

To determine above ground biomass in the cottonwood cover type, 10 whole trees were harvested in mid-September of each year. This mid-September sampling allowed the collection of samples prior to any foliage loss due to annual leaf drop. Trees were harvested at random across the study site with an effort being made to represent the range in tree size. Harvested trees were cut at ground level, and divided into stem, leaf, and branch components. Each component was weighed in the field and sub-samples taken for fresh weight to dry weight conversion and chemical analysis. Leaf samples were oven dried for 48 h at 60°C, while stem and branch samples were dried for 120 h. Leaf and woody tissue sub-samples were then ground in a Wiley mill to pass a 1-mm screen and stored in sealed plastic jars. Harvested trees were used to establish an allometric relationship between above ground biomass and stem diameter at 1.2 m above the soil surface. In the late fall of each year the diameter of all trees occurring in each of the five blocks were measured and an estimate of total above-ground biomass calculated based on the weight relationships established with the destructive harvests.

Sampling of below ground biomass

Using a tractor mounted Giddings probe (Giddings Machine, Fort Collins, CO), soil cores were collected in 5.0-cm diameter plastic sleeves to a depth of 120 cm. Samples were collected from the central portion of each of the clipped plots. Tube ends were capped and the samples were returned to the laboratory and stored at 4°C. Each core was dispersed in tap water and the roots collected using methods described by Kelly and Ericsson (2003). After determining the fresh weight, samples were oven dried at 60°C for 48 h and ground in a Wiley mill to pass a 1-mm screen.

Sampling of roots in the cottonwood cover type required a different sample collection procedure. On each sampling date, five trees were chosen at random in each of the five blocks. A sample was collected at random at points 0.5 and 1.0 m from the stem of each of these trees. The remainder of the sample processing procedure

was the same as that used for the herbaceous communities. Sampling depth in all cover types was increased to 240 cm in 2004.

Root surface area

Calculations of smooth brome, switchgrass, and cottonwood root surface area were made for all samples collected during 2001. Roots were separated from the soil as described above and frozen after the fresh weight determination. Total root length of each sample was then determined using the line intercept method of Tennant (1975). Mean root radius was calculated based on the fresh weight using the method described by MacKay and Barber (1985). These two measurements were combined to calculate total root surface area. Root surface measurements for the alfalfa–smooth brome cover type were made in 2003. In subsequent years the allometric relationship established between root surface area and root dry weight in the 2001 smooth brome, switchgrass, and cottonwood samples was used to estimate total root surface area in the 2003 and 2004 root samples while the 2003 alfalfa–smooth brome measurements were used to provide alfalfa root surface estimates in 2004.

Chemical analysis of plant tissue

Because of the small amount of material present in many of the root samples, it was necessary to composite samples in order to have a sufficient weight of material for analysis. For each herbaceous cover type, samples from the two replicate locations within a block were combined to create a single sample for analysis. Root samples from the cottonwood cover type were composited by combining the roots from the five 0.5-m samples within a block into one sample. Similarly, all of the 1.0-m samples within a block were combined to form a second sample for elemental analysis. For analysis, plant samples were digested using a nitric acid–peroxide method according to procedures described by Mills and Jones (1996) and analyzed by inductively coupled plasma emission (ICP) (Greensburg et al. 1995).

Soil sampling and analysis

At the time the buffer was established, soil samples were collected from areas on both sides of the drainage way. Samples were collected with a 3.18-cm diameter hand probe to a depth of 30 cm. Cores were divided into 0–5 cm, 5–15 cm, and 15–30 cm depth increments. To determine the initial soil chemical properties, the samples were air dried, sieved to 2-mm particle size, and analyzed for extractable P (Bray-1; 2 g soil extracted with 20 ml of 0.025 M HCl + 0.03 M NH_4F and shaken for 5-min), exchangeable K, Ca, and Mg, pH and organic matter content by the methods outlined in Brown (1998). These initial properties are given in Table 1. A second set of soil samples was collected from areas on both sides of the drainage way after the fourth growing season to evaluate any changes in extractable soil P.

Data handling and statistical analysis

The mixed procedure in SAS Version 9.1 (2004) was used for the data analysis. This experiment was treated as a randomized complete block design, with fixed blocks and random block by vegetative cover type, block by year, and block by vegetative cover type by year interactions. The Satterthwaite correction for degrees of freedom was used to preserve the type I error rate of the tests if variances of observations at different levels of cover type or year were different. From an examination of plots of the residuals, these variances did not appear to be the same. The block to block differences of effects were used as the error terms for testing the vegetative cover type, year, and year × vegetative cover type effects. For testing the differences among vegetative cover types in the same year, and between years of the same vegetative cover type, the least squares means (lsmeans) option was used. This option estimates the means at levels of the treatments and variances of these means. The ''diffs option'' estimates the difference of these means and tests the significance of these differences. Since many comparisons were made, the Bonferroni correction for multiple corrections was used to hold the type I error rate at 0.05 for

Table 1 Initial chemical properties in the surface layers of Kennebec silt loam and Napier silt loam at the USDA-ARS Deep Loess Research Station

Soil	Depth (cm)	Bray-1P (mg kg^{-1})	Exch. K (mg kg^{-1})	Exch. Ca (mg kg^{-1})	Exch. Mg (mg kg^{-1})	pH	Organic matter %
Kennebec sil	0–5	36	201	2749	337	7.7	3.6
	5–15	36	205	2737	333	7.7	2.7
	15–30	22	157	2620	344	7.6	2.4
Napier sil	0–5	44	236	2511	258	7.3	4.8
	5–15	42	203	2109	250	7.1	3.2
	15–30	17	167	2302	268	7.1	2.4

Kennebec soil is found in the multi-species buffer, and Napier is found in the smooth brome control area

testing all vegetative cover type differences and for testing all year differences. The same general statistical approach was used for comparison of the 2001 and 2004 soil samples with the addition of depth as a variable.

Results

Biomass estimates

End of growing season total biomass estimates for the alfalfa and switchgrass cover types generally increased during the study period, with the largest increase (4.5-fold) occurring in the switchgrass cover type (Fig. 2). The amount of above ground biomass in the previously established smooth brome cover type remained relatively constant across the study period, while root biomass fluctuated somewhat, even though the stand had been in existence for more than 37 years. Overall, biomass in the smooth brome and alfalfa cover types did not change significantly (Table 2). The switchgrass community exhibited above ground increases across the 4-year study period. The increase in root biomass depicted for all three herbaceous cover types in the fourth year of study (Fig. 2) is due in part to an increase in root sampling depth from 120 to 240 cm in 2004.

During the 2003 growing season, shoot and root biomass samples were collected on four occasions to evaluate changes in the total standing plant biomass present in each of the three herbaceous cover types (Fig. 3). Alfalfa biomass increased in May through August, then stabilized in September. Switchgrass biomass increased throughout the growing season, while the smooth brome community reached its peak in August (Fig. 3) and declined by 37% by the time of the September sampling.

Mean total cottonwood biomass on an area basis for each of the 4 years of the study reflects relatively slow growth in the first and second year of the study and then a substantial increase in biomass during the third and fourth years (Fig. 2). On a per tree basis, biomass increased from a mean of less than 0.2 kg of above ground biomass at the end of the first growing season to approximately 9.3 kg at the end of fourth growing season.

Root surface area

Based on the September samples, root surface area of the alfalfa, smooth brome, and switchgrass (Fig. 4) did not increase as rapidly during the 4-year study period as that observed for above ground biomass. Even though smooth brome root biomass exhibited some degree of increase, root surface area actually remained relatively constant when the fact that sampling depth was doubled for the 2004 sample is taken into consideration. Both the alfalfa and switchgrass communities exhibited substantial increases compared to smooth brome, with the switchgrass producing the highest level of root surface area (36.0 m^2 m^{-3}) at the time of the final sampling in 2004. It also appears that root surface area of the switchgrass had stabilized by the end of the 2003 growing season (Fig. 4).

Estimates of root surface area collected across the 2003 growing season varied among cover types (Fig. 5). The alfalfa values suggest alternate periods of increase followed by declines of

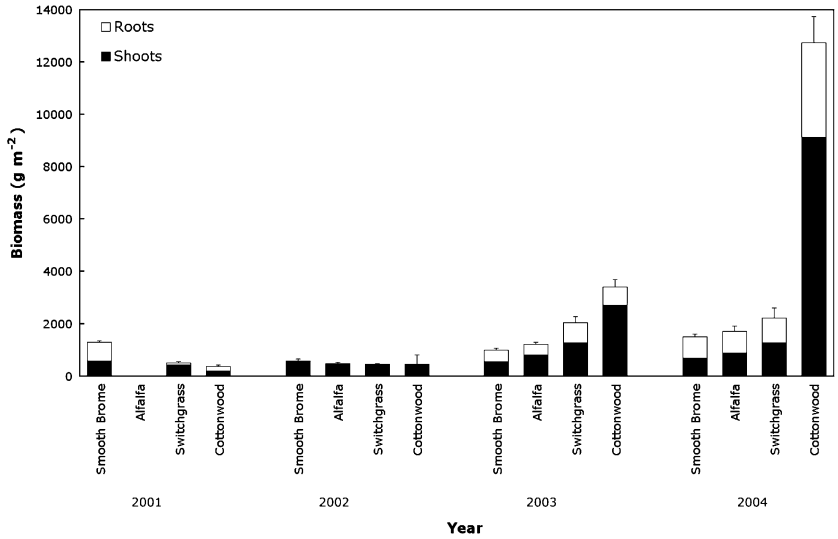

Fig. 2 Standing crop of shoot and root biomass for the smooth brome, alfalfa, switchgrass, and cottonwood vegetative cover types in a multi-species riparian buffer at the USDA-ARS Deep Loess Research Station at the end of the 2001 through 2004 growing seasons. Root biomass values in 2001–2003 are to a depth of 120 cm. Sampling depth in 2004 was increased to 240 cm. Root and shoot biomass was not determined for the alfalfa cover type in 2001 due to poor stand development. Root biomass was not sampled in any of the three cover types in 2002. Error bars represent the standard error of the mean

approximately 30%. Comparison of alfalfa root surface area at the start of the 2003 growing season (23.5 m^2 m^{-3}) with the value at the end of the growing season (15.8 m^2 m^{-3}) indicates a 33% reduction in the amount of root surface area present in the stand. Smooth brome values were relatively constant for the May and June sample dates, then increased by approximately 22% in August and then declined by 58% in September. Switchgrass values remained relatively constant from mid-May through mid-August (Fig. 5), and then increased by approximately 30% to 38.5 m^2 m^{-3} at the time of the September sample.

Cottonwood root surface area during the 2003 growing season (Fig. 5) declined by 46% from a high of 51.4 m^2 m^{-3} in May to 27.8 m^2 m^{-3} in September. Figure 4 illustrates the substantial changes in cottonwood root surface area that occurred over the 4 years of the study. The increase between 2003 and 2004 is in part attrib-

Table 2 Summary of results from statistical comparisons of total biomass between cover types in the fourth year (2004) of the study and comparisons of total biomass within a cover type in the initial year (2001 or 2002) of study versus the fourth year (2004)

Comparison of total biomass between cover types—2004					
Smooth brome versus alfalfa	0.79	Alfalfa versus switchgrass	0.52	Switchgrass versus cottonwood	<0.01*
Smooth brome versus switchgrass	0.37	Alfalfa versus cottonwood	<0.01*		
Smooth brome versus cottonwood	<0.01*				
Comparison of initial year biomass versus final year biomass					
Smooth brome		2001 versus 2004		0.81	
Alfalfa		2002 versus 2004		0.12	
Switchgrass		2001 versus 2004		0.03*	
Cottonwood		2001 versus 2004		<0.01*	

Shoot biomass, root biomass, root surface area, and plant phosphorus content exhibited the same patterns of statistical significance as those depicted for total biomass. The 0.05 probability level was used as the decision point for statistical significance

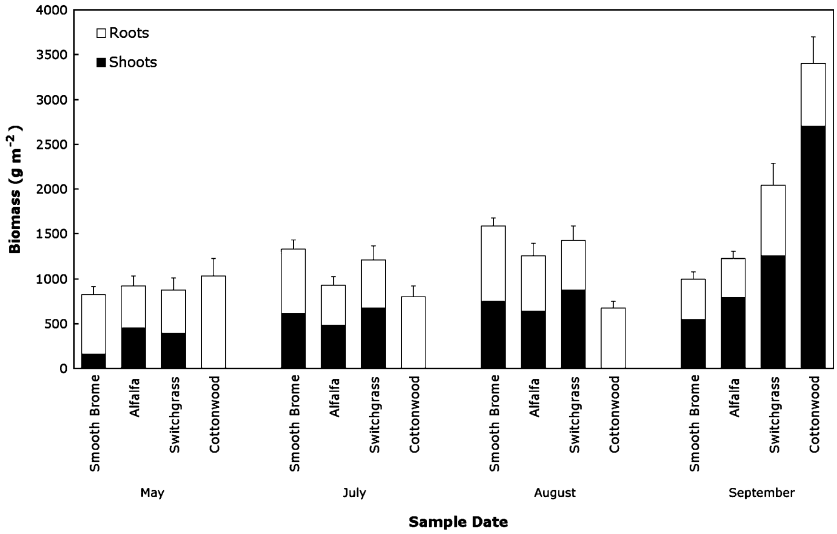

Fig. 3 Standing crop of shoot and root biomass for the smooth brome, alfalfa, switchgrass, and cottonwood vegetative cover types in a multi-species riparian buffer at the USDA-ARS Deep Loess Research Station on four occasions across the 2003 growing season. Root biomass was sampled to a depth of 120 cm. Error bars represent the standard error of the mean

utable to the increase in sampling depth to 240 cm, but nevertheless represents an almost 5-fold increase in root surface area during a time of rapid tree growth overall (Fig. 2).

P accumulation in plants

Plant P per unit area in the switchgrass cover type in 2001 was strongly biased toward the shoot component (Fig. 6). However, by the end of the 2003 growing season the content of P in the plants growing in the alfalfa and switchgrass cover types was approximately 60% in roots and 40% in shoots. Smooth brome P was almost equally divided between roots and shoots. With the increase in root sampling depth to 240 cm in 2004, the relative distribution of P in roots versus shoots did not change appreciably for the alfalfa and switchgrass, while the smooth brome split changed to 55% in roots and 45% in shoots. By

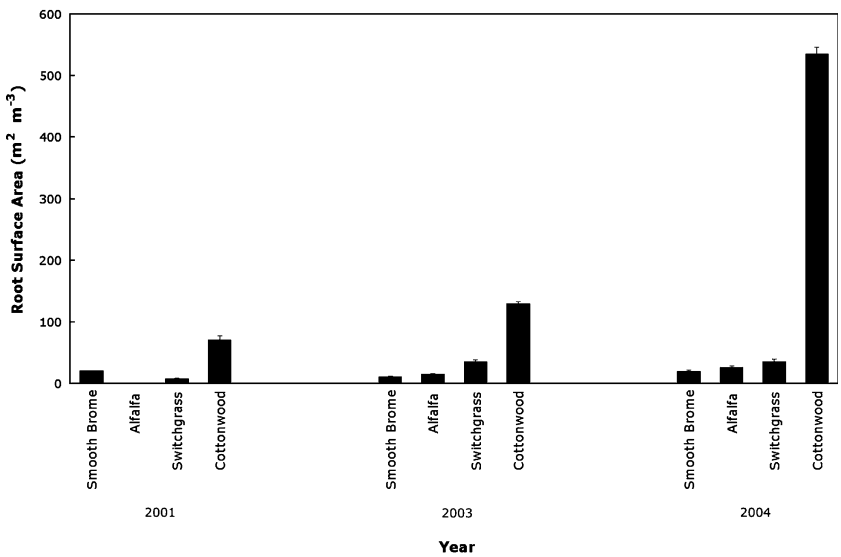

Fig. 4 Estimates of total root surface area for the smooth brome, alfalfa, switchgrass, and cottonwood vegetative cover types in a multi-species riparian buffer at the USDA-ARS Deep Loess Research Station at the end of the 2001, 2003, and 2004 growing seasons. Values for 2001 and 2003 are based on a sampling depth of 120 cm. Sampling depth in 2004 was increased to 240 cm. Root surface area for the alfalfa cover type was not determined in 2001 due to poor stand development. Error bars represent the standard error of the mean

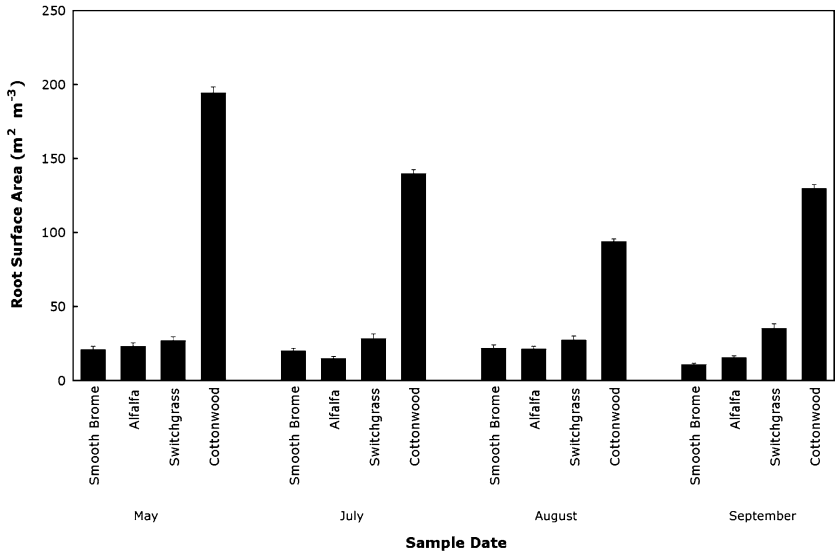

Fig. 5 Estimates of total root surface area for the smooth brome, alfalfa, switchgrass, and cottonwood vegetative cover types in a multi-species riparian buffer at the USDA-ARS Deep Loess Research Station on four occasions across the 2003 growing season. Root biomass was sampled to a depth of 120 cm. Error bars represent the standard error of the mean

the end of the 2003 growing season, the pattern observed in the cottonwood cover type (Fig. 6) differed somewhat from that of the herbaceous cover types with the amount of P present in the above ground portion of the plant continuing to be greater than that in the roots. Although the absolute amount of P in the root component increased in 2004 when the sampling depth was doubled, the relative distribution of P continued to be strongly biased toward the shoot (Fig. 6).

Patterns of P accumulation across the 2003 growing season varied by cover type (Fig. 7). Switchgrass P content increased steadily throughout the growing season in concert with total plant

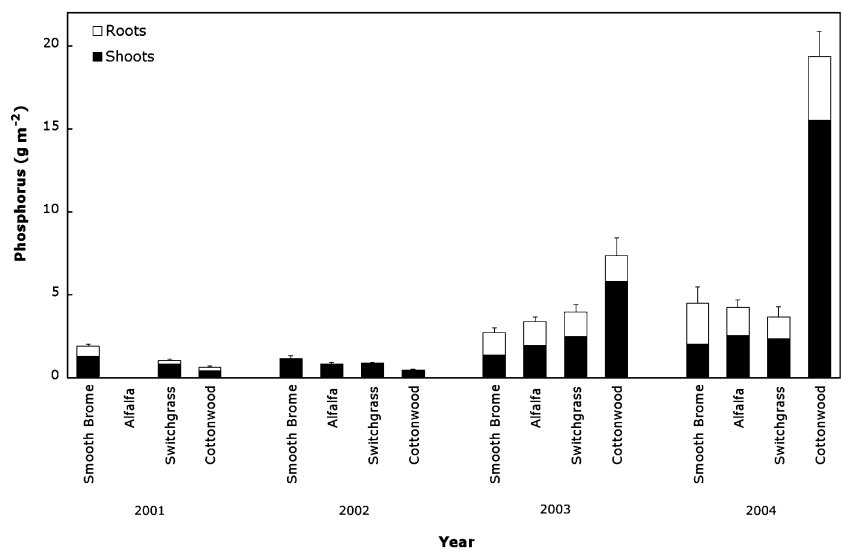

Fig. 6 Standing pools of phosphorus (P) in the shoots and roots of plants growing in the smooth brome, alfalfa, switchgrass, and cottonwood vegetative cover types in a multi-species riparian buffer at the USDA-ARS Deep Loess Research Station at the end of the 2001 through 2004 growing seasons. Root P values in 2001–2003 are to a depth of 120 cm. Sampling depth in 2004 was increased to 240 cm. Root and shoot P were not determined for the alfalfa cover type in 2001 due to poor stand development. Root P was not sampled in any of the three cover types in 2002. Error bars represent the standard error of the mean

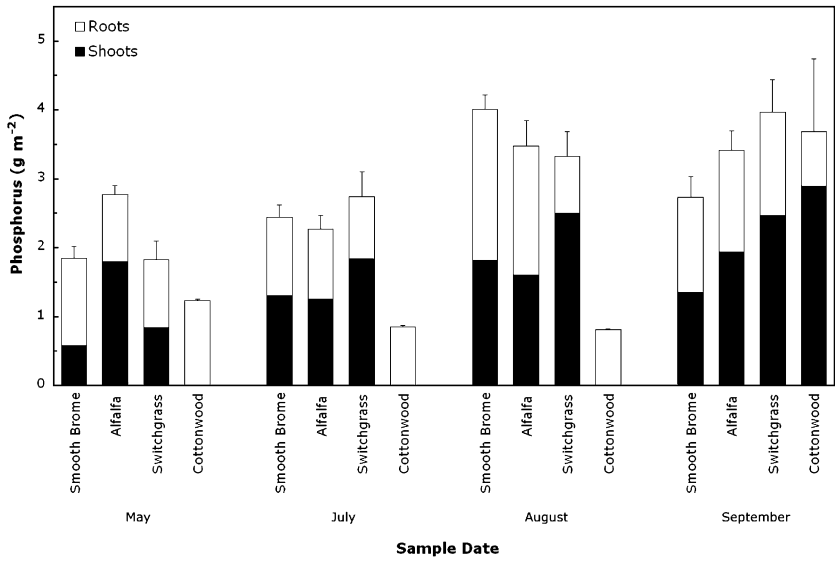

Fig. 7 Mean phosphorus content of shoots and roots growing in the smooth brome, alfalfa, switchgrass, and cottonwood vegetative cover types in a multi-species riparian buffer at the USDA-ARS Deep Loess Research Station across the 2003 growing season. Above ground biomass in the cottonwood cover type was determined only at the time of the September sampling. Root biomass values are to a depth of 120 cm. Error bars represent the standard error of the mean

biomass. Smooth brome P increased through August, then declined in September. This response is again consistent with the pattern observed for total biomass. Plant P per unit area in the alfalfa cover type did not correspond directly with the pattern of biomass accumulation (Fig. 3) with a decline in P content being observed in the July sample, followed by an increase in the August and September samples. Values for cottonwood root P across the 2003 growing season declined slightly as the season progressed (Fig. 7) and in most cases were less than or equal to the amount of root P in the other three cover types.

Extractable P in the soil

Based on the soil test results (Table 1), soil pH and nutrient levels were adequate for the growth of the four species in both the Kennebec and Napier soils (Sawyer et al. 2002). Initial P levels were very high, but not excessive. In addition, both soil pH and the levels of other nutrients were adequate for the growth of the four species. Extractable P in the 0–5 and 5–15 cm layers of the Kennebec soil was greater ($P = 0.03$) than that in the 15–30 cm layer. A similar trend was observed with the Napier soil. After four growing seasons, extractable P levels changed little in the two soils, regardless of plant species (Table 3). Extractable P tended to increase in the 0–5-cm layer, and decrease in the 5–15 and 15–30-cm layers; however, changes were not statistically significant. As a point of comparison, initial extractable P levels in the adjacent cropland averaged 44 mg kg^{-1} in the 0–5 cm-depth and 19 mg kg^{-1}in the 5–15-cm depth. During the course of the study, soil solution levels of P as determined by the analysis of samples collected with cup lysimeters located at a depth of 1.4 m, ranged from 0.02 to 0.1 mg l^{-1} (M. D. Tomer, 2006, Personal Communication). In addition, Wang et al. (2004) found the equilibrium soil solution P concentration in the rhizosphere in a laboratory study of the Kennebec soil to on the order of 1.0 mg l^{-1}. Unpublished results from a preliminary field study in the cottonwood cover type using similar sampling methodology to that described in Wang et al. (2004) found that P concentration in discrete samples of rhizosphere solution collected in situ ranged from 0.02 to 2.58 mg l^{-1} depending on proximity to roots and depth of the sampling site. Because of the significant spatial heterogeneity of soil solution P, no attempt was made to monitor changes within each cover type during the 4-year period.

Discussion

At the end of 4 years, the peak amount of biomass present in the alfalfa, switchgrass, and

Table 3 Extractable P (Bray-1) by plant cover type in the surface layers of Kennebec silt loam and Napier silt loam following a period of 4 years of biomass production

Profile depth (cm)	Cover type			
	Smooth brome (Napier) (mg kg^{-1})	Alfalfa (Kennebec) (mg kg^{-1})	Switchgrass (Kennebec) (mg kg^{-1})	Cottonwood (Kennebec) (mg kg^{-1})
0–5	53a (+9)	43a (+7)	44a (+8)	38a (+2)
5–15	38ab (–4)	30b (–6)	31b (–5)	25b (–11)
15–30	22b (+5)	21c (–1)	20c (–2)	18c (–4)

Kennebec soil is found in the multi-species buffer, and Napier is found in the smooth brome control area. Within a column, values followed by the same letter are not significantly different at the 0.05 level. Values in parentheses indicate a numerical increase (+) or decrease (–) from initial levels for that soil type (Table 1)

smooth brome control cover types was of similar magnitude (Fig. 2), while the amount of biomass present in the cottonwood cover type was an order of magnitude greater (Fig. 2). These data also indicate that the smooth brome control cover type which had been in place for several years had reached a level of stability in terms of the amount of biomass produced each year while there is at least a suggestion that the alfalfa and switchgrass communities have the potential to continue to increase to a higher level of production before stabilization occurs. While this is speculative, the continued upward trend in the data at the end of four growing seasons seems supportive of this conjecture.

The relatively slow growth of the cottonwood trees during 2002 was largely a direct result of a substantial amount of deer browse damage that occurred during the winter of 2001–2002. The trees began to recover from this damage in 2003 and continued the recovery into 2004. A qualitative comparison of trees that had been browsed with those that had not, indicated that a much higher average level of biomass production across the site would have been realized by the trees had this damage not occurred. Stanturf et al. (2001) reported leafless above ground biomass for 10-year-old cottonwood, grown at a slightly larger spacing (3.7×3.7 m) than used in the current study, to range from 6.7 to 12.5 tons ha^{-1} across a variety of sites. More directly comparable to the current study are the results of Coleman et al. (2004) who found root and shoot biomass at the end of 2 years to range from 1034 to 1452 g m^{-2} in a stand with a 1×1 m spacing. Both studies suggest the results reported from the current study fall within the range previously reported in the literature. One very important practical lesson learned from this study is that in areas where deer populations are high and woody browse is limited, it is important to protect the developing trees from browsing during the first couple of years of growth. Visual observations suggest that as much as 25% of the cottonwood biomass potential was lost during the first four years as a result of deer damage.

A second factor that seemed to influence the production of the trees was the presence of an extremely dense soil layer in the northern most block of the study area. Soil bulk density in the 5–15-cm layer increased from 1.25 mg m^{-3} in block 1 on the southern end to 1.42 mg m^{-3} in the block 5 on the northern end of the study area (Fig. 1). Trees growing in this area were noticeably shorter and thus produced less biomass probably as a result of reduced water availability late in both the 2003 and 2004 growing seasons. This effect was less obvious in the herbaceous cover types.

Phosphorus capture by the vegetation differed substantially when the herbaceous cover types are compared to the cottonwood values (Fig. 6). The P content of the cottonwood trees was an order of magnitude higher at the end of the 2004 growing season. This difference appears attributable to the level of biomass production as well as the differences in root surface area between the herbaceous cover types and the cottonwood trees. Based on both greenhouse and field data for 30 cultivars of switchgrass, Missaoui et al. (2005) report that switchgrass can exhibit considerable variability in P concentration with levels ranging

from 2.8 to 9.8 g kg^{-1}. Recent work by Clark (2002) indicates these differences can be attributed in part to the combined influence of differences in mycorrhizal species and root surface area. Comparison of the root surface area values near the end of the 2004 growing season for the herbaceous cover types with those of the cottonwood trees (Fig. 4) indicates values greater by a factor of 15 or more for the cottonwood. Similarly, Tibbets and Molles (2005) report foliage P concentrations in naturally occurring cottonwood to range from approximately 0.5 to 2.5 g kg^{-1} depending on sampling site and time of sample collection. Both of these reports indicate the potential for variation in P uptake as a function of site factors.

After four growing seasons, extractable P levels changed little in the two soils, regardless of plant cover type (Table 3). This is not surprising, given that plant biomass was not removed from the site during the course of the study. Extractable P tended to increase in the 0–5-cm layer, and decrease in the 5–15-cm layers; however, the changes were not statistically significant. This tendency may reflect a positive balance between P input from the decomposition of leaf and branch tissue on the soil surface and P uptake by the plant. The negative P balance of the 5–10-cm layer may be attributable to a greater P uptake in that zone relative to input.

If the management goal is to minimize P transport to surface waters by plant capture, then it will be essential to have a system in place that will allow the P captured in above ground plant parts to be removed from the site periodically in order to sustain and maximize the capture potential. Otherwise, it is likely that the herbaceous cover types will come to equilibrium fairly quickly and P uptake on a seasonal basis will be equal to return, when plant biomass levels reach relative stability. Thus herbaceous cover types need to be harvested at least annually after the stand is fully established in order to sustain export of P over the longer term and to continuously deplete soil solution P. Depending on species and growing conditions, it may be possible to harvest and remove the accumulated P on two occasions thus allowing more P to be captured as a consequence of biomass removal and plant growth stimulation. Although most government subsidy programs in the U.S. do not allow harvest to occur, doing so would make the buffer even more efficient as a means of nutrient capture.

The fact that cottonwood trees accumulate more P in the above ground portion of the plant than in the roots as compared to the herbaceous species may lead to the export of more P in the woody tissue in the long term. Although harvesting the cottonwood trees on an annual basis would not be desirable or practical, it is possible that regular harvests as wood chips on a 7- to 10-year cycle would allow appreciable amounts of P to be captured and then removed in the woody portion of the tree. The chips could provide an additional source of income to the land owner and thus encourage the long term retention of the buffer. Again this would require a change in current administrative policy, but the improvement in P capture over the long term would be environmentally beneficial.

It would not be desirable to harvest the trees during the growing season, since doing so would likely limit the ability of the stand to regenerate itself through vegetative means. A non-growing season harvest would allow for several harvest cycles before the stand would need to be replanted. Thus, the P captured annually in the leaves of the tree would not be exported but recycled to the soil surface in annual litterfall. Nevertheless, P retained on site in leaves would help to slow the loss of P during the growing season as the canopy expands and the mass of leaves increases each year. Decomposition rates and precipitation patterns would play an important role in determining how quickly the P from the leaf pool would become available for subsequent plant uptake or removal due to leaching loss.

With the data available, it is possible to do a preliminary calculation of the amount of P that could be exported via harvest from the site over a 4-year cutting cycle. To make this calculation, it is necessary to make the simplifying assumption, based on the whole tree harvests, that 56% of the weight of above ground P in the cottonwood trees is in the harvestable woody portion of the plant (stem + branches). It is also necessary to assume that the weight of P in above ground

plant parts in the alfalfa and switchgrass cover types would be the same value for all 4 years of the calculation as they were in 2004. With these simplifying assumptions and prorating the relative area of each cover type to the total area of the buffer on a per hectare basis, the total amount of P removed by harvest during a 4-year period would be approximately 101 kg ha^{-1} (alfalfa 20 kg ha^{-1}, switchgrass 19 kg ha^{-1}, and cottonwood 62 kg ha^{-1}). This compares to a cumulative harvest of approximately 62 kg ha^{-1} for the smooth brome control, using the 2004 above ground P value for smooth brome for each of the four years. This represents a 63% increase in P export over that possible with the smooth brome control. As a point of comparison, P concentration in fertilized smooth brome foliage growing in a 10-year-old South Dakota stand was found to vary in concentration from 1.8 to 2.0 g kg^{-1} with an average above ground dry matter yield of 5185 kg ha^{-1} (Gelderman et al. 2002). These values would yield an annual removal of P on the order of 9.9 kg ha^{-1}in a single harvest. Phosphorus concentrations over a 3-year period in irrigated pure alfalfa stands have been reported by Berrada and Westfall (2005) to average 2.4 g $kg^{-1}$for a range in P additions. Marino and Berardo (2005) found a 4-year, cumulative removal of P by alfalfa, to total 61 kg ha^{-1} without any direct addition of P. This is approximately three times the amount removed in the alfalfa cover type over a similar time frame, but it should be noted that the alfalfa cover type in the current study was strongly dominated by smooth brome by the 4th year of the study. By comparison, Fail et al. (1987) and Lowrance et al. (1997) report typical values for P accretion by the above ground woody portion of a variety of riparian forests to be on the order of 2–7 kg ha^{-1} $year^{-1}$. Values from the current study are substantially greater, averaging slightly more than 15 kg ha^{-1} $year^{-1}$. This difference may be attributable in part to species difference as well as the closer spacing of individual trees in the buffer.

If a longer cutting cycle is projected, the cottonwood contribution will continue to increase at a much faster rate than is likely for the herbaceous cover types. Thus, the addition of a fast growing woody species enhances the capture and export of P when compared to a herbaceous buffer only.

While not the focus of this study, one of the positive aspects of having a continuous vegetative cover, in addition to its ability to capture nutrients through plant uptake, is the positive impacts organic additions have on rebuilding soil structure in formerly cultivated soils (Marquez et al. 1999). However, Heathwaite et al. (2005) have reported that P associated with colloids can move freely and quickly through larger soil pores while P in solution appears to diffuse into soil micropores where it is retained. Thus, one could speculate that while a vegetative buffer can have positive impacts on direct nutrient retention in vegetation, it may also increase the movement of colloidal P through its impacts on the development of macropores. Likewise, Koopmans et al. (2004) and others (Barrow 1983; van der Zee et al. 1987) have speculated on the relative balance between solution and solid phase P and the importance of the relatively slow rate of P diffusion both into and out of soil aggregates as an important controlling mechanism for total plant capture of P. It may well be that in some cases plant demand exceeds the bioavailability of P (Koopmans et al. 2004). The relative balance of these two processes is an important question that warrants further investigation.

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